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Transient Heat Transfer through Protective Clothing at Sea Level and High Altitude

U S ARMY RESEARCH INSTITUTE OF ENVIRONMENTAL MEDICINE

Natick, Massachusetts

July 1995

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UNITED STATES ARMY
MEDICAL RESEARCH AND MATERIEL COMMAND

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Skin, clothing and dew point temperatures were measured on subjects walking and then resting on a treadmill, wearing U.S. Army BDU and BDO (MOPP 1). Sea level and a high altitude environment were tested. The altitude environment, comparable to the condition at terrestrial elevation of 4,570 m (15,000 ft) above sea level, was simulated in the U.S. Army Research Institute of Environmental Medicine (USARIEM) Hypobaric Chamber. For both environments, we found a marked increase in the weighted average clothing temperature, $\bar{T}_{cl}$, during the transient period immediately after the cessation of walking. The similarly weighted average skin temperature, $\bar{T}_{sk}$, did not exhibit any corresponding change, thus eliminating a metabolic origin of the observed increase in $\bar{T}_{cl}$. Moreover, since the same effect was found at both sea level and altitude, hypobaria also must not be a primary cause. A large release of heat stored within clothing is suggested as a source. When walking ceased, this stored heat, resident within the air mass between clothing layers, was driven outward by the large temperature gradient between skin and ambient temperatures. Other alternative mechanisms such as the pumping effect of clothing and the regain phenomenon were also examined and discussed.

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Transient Heat Transfer through Protective Clothing at Sea Level and High Altitude

by

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JULY 1995

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EXECUTIVE SUMMARY

Skin, clothing and dew point temperatures were measured on subjects walking and resting on a treadmill, wearing U.S. Army Battledress Uniform (BDU) and U.S. Army chemical protective Battledress Overgarment (BDO) in MOPP 1 configuration. Both sea level and a simulated altitude environments were tested. The simulated altitude environment, comparable to the condition at terrestrial elevation of 4,570 m (15,000 ft) above sea level, was created in the U.S. Army Research Institute of Environmental Medicine (USARIEM) Hypobaric Chamber. For both environments, we found a marked increase in the weighted average clothing temperature, $\bar{T}_{cl}$, during the transient period immediately after the cessation of walking. The similarly weighted average skin temperature, $\bar{T}_{sk}$, did not exhibit any corresponding change, thus eliminating a physiological origin of the observed increase in $\bar{T}_{cl}$. Moreover, since the same effect was found at both sea level and altitude, hypobaria also must not be the primary cause. A large release of heat stored within clothing is suggested as a source. When walking ceased, this stored heat, resident within the air mass between clothing layers, was driven outward by the large temperature gradient between skin and ambient temperatures. Other alternative mechanisms such as the pumping effect of clothing and the regain phenomenon were also examined and discussed.

INTRODUCTION

This study examines how clothing insulation affects the heat exchange between skin, clothing and the ambient environment during the transient phase after steady activity ceases. Both U.S. Army Battledress Uniform (BDU) and U.S. Army chemical protective Battledress Overgarment (BDO) were studied. During a period of constant activity, a steady state is established as a result of the interaction between heat exchange mechanisms and clothing insulation. When the activity stops, this equilibrium is disrupted. In the transient period immediately following the cessation of activity, the heat exchange mechanisms within and without clothing layers are suddenly altered. Skin and clothing temperatures readjust to a new steady state. How do clothing insulation and barometric pressure affect the heat exchange mechanisms during this transient period?

Multi-layered clothing ensembles create resistance to both sensible and insensible heat transport for humans. Dry heat transport through a textile layer involves convection and radiation in the interstices between the fibers and through conduction by the fibers themselves [Woodcock, 1962a]. Resistance to dry heat transport is primarily determined by the amount of air trapped inside the layers and the flow of outside air at the outer surface of the ensemble [Gagge & Nishi, 1977]. A large volume of trapped air will result in a high thermal resistance. However, if air in the interstices between the fibers is replaced by molecular water, particularly from heavy sweating during exercise, the thermal resistance of the clothing ensemble is reduced due to the higher thermal conductivity of water.

Barometric pressure (P_b) also has an effect on the heat transfer characteristics of clothing ensemble. P_b has pronounced effects on air density and mass diffusivity, which in turn change the convective and evaporative heat transfer processes. It is known that as P_b decreases, convective heat transfer diminishes [Chang et al. 1990]. Also, the evaporative transfer mechanism appears to be enhanced [Gonzalez et al. 1985]. While the evaporative heat transfer does not alter clothing insulation directly, evaporative heat loss does affect skin and clothing temperatures, thus indirectly influencing clothing insulation. The efficacy of evaporative heat transfer increases with elevations in altitude. Furthermore, insulation of air, trapped between clothing layers and at the clothing-skin boundary layer, increases with decreasing P_b [Gonzalez, 1987].

While many reports are available on the relationship between temperature, clothing insulation and exercise, most of these reports addressed only steady state conditions at sea level. In a typical steady-state study, subjects were asked to exercise on treadmill [Havenith et al. 1990; Nielsen et al. 1985] or bicycle [Vogt et al. 1983]. Olesen et al. [1982] used a movable manikin to simulate exercise on a bicycle ergometer. Pertinent data were collected after steady state had been reached. These steady-state data were then compared to corresponding sedentary data such as from standing or sitting. We looked at clothing temperature and clothing insulation data as subjects exercised and subsequently rested on a treadmill. Both the steady-state condition and transient data were recorded continuously.

METHODS

CHAMBER

The U.S. Army Research Institute of Environmental Medicine (USARIEM) Hypobaric Chamber was used for both sea level and altitude testings. Sea level testing was conducted at P_b of 760 ± 10 Torr (mmHg) atmospheric pressure (sea level barometric pressure at USARIEM on the test days). The altitude environment was simulated by decreasing the ambient atmospheric pressure to 429 ± 1 Torr in the hypobaric chamber. The 429 Torr environment is comparable to conditions at a terrestrial altitude of 4,570 m (15,000 ft) above sea level. For both testing environments, the ambient temperature within the chamber was maintained at 22.0 °C, with relative humidity at 50%. The wind speed within the chamber was maintained at 1.0 m/s with the aid of a circulating fan. The air velocity was measured with a cup anemometer. The chamber temperature was measured at two points (on opposite sides of the treadmill) with copper-constantan thermocouples.

SUBJECTS

Eight males, between the ages of 18 to 23, served as volunteer subjects. The volunteers received a verbal briefing on the purpose, procedures and risks of the study, and each signed an informed consent agreement. Each volunteer received a medical

clearance from a medical officer. All testing procedures conformed to the U.S. Army Regulation AR 70-25, Use of Volunteers for Research.

The physical characteristics of average height, weight, body (Dubois) surface area, and maximum $\dot{V}O_2$ of the subjects are shown below ($\dot{V}O_2$ data extracted from the subjects' recent historical database).

Height (m)	Weight (kg)	Body Surface Area (m^2)	Maximum $\dot{V}O_2$ (l/min)
1.77 ± 0.11	77.6 ± 9.6	1.95 ± 0.18	4.28 ± 0.53

CLOTHING ENSEMBLES

The U.S. Army temperate zone BDU consists of a coat and trousers. The uniform is loose fitting to allow body ventilation. The material is a 50/50 nylon/cotton twill, weighing 234 g/m^2 (7 oz/yd^2). The exterior print pattern is four-color woodland camouflage. The BDU was worn with the Army regular issue leather combat boots. The BDO is a two-layer garment of coat and trousers. The outer fabric shell is a 50/50 nylon/cotton twill, with a durable water-repellent to repel liquid agents. This outer shell is laminated to an inner layer of polyurethane foam liner impregnated with activated carbon. The outer layer pattern is either olive green or four-color woodland camouflage.

In this study, the MOPP 1 configuration was employed in which the BDO was worn without the chemical protective mask, rubber gloves or rubber overboots. Moreover, the BDU was worn over cotton underwear, and the BDO was worn over the BDU. As a baseline condition, a nude (or unclothed) configuration, with the subjects wearing only gym shorts and gym shoes, was also studied.

STUDY DESIGN

The study scenario is described by the following steps.

1. Hydration - 400 ml. water (as a measure to prevent dehydration).
2. Dress and instrumentation.

3. Enter chamber.
4. Decompression of chamber to 4,570 m. condition (approximately 7.5 minutes), for hypobaric sessions.
5. 10 minute resting period while standing on the treadmill.
6. Walking at constant speed of 1.34 m/s (3 mph) on the treadmill for 45 minutes.
7. 10 minute cool-down period while standing on the treadmill.
8. Chamber recompression back to sea level condition (approximately 7.5 minutes), for hypobaric sessions.
9. Exit chamber.
10. Undress.

INSTRUMENTATION

The instrumentation phase consisted of attaching probes for measuring skin, clothing, dew point, and rectal temperatures, plus sensor for heart rate and blood oxygen level.

Temperature Measurements

On the subjects, corresponding temperatures were measured from both inside and outside of the clothing ensemble, at approximately the same location, to determine the parameters across the clothing. Regional skin temperatures (T_{sk}) on the forehead, chest, back, upper arm, lower arm, thigh and lower leg were monitored. At these same sites, regional clothing temperature, T_{cl}, were measured on the outer surface of the clothing ensemble. T_{sk} and T_{cl} were measured using copper-constantan thermocouples. At the chest site, the skin and clothing dew point temperatures were measured with dew point temperature sensors [Graichen et al. 1982] similarly placed on the inside (skin surface) and outside (clothing surface) of the uniform ensemble. For the nude configuration, only a skin dew point sensor was used. The body core (rectal) temperature (T_{re}) was monitored with a 10 cm rectal temperature probe. All temperature data were collected at three-second intervals, using a personal computer system.

Other Measurements

Each subject wore a light-weight oxygen (O_2) mask at all testing sessions. The O_2 flow rate was adjusted such that the subject's blood O_2 content was approximately equivalent to that at a sea level condition. The blood oxygen level was monitored with a stand-alone finger tip blood saturation monitoring system. The monitor also measures the heart rate simultaneously. The heart rate and blood oxygen level were displayed continuously and recorded at 10-minute intervals.

The O_2 mask was worn in both sea level and altitude testing sessions. It is expected that in a hypobaric environment, the expiratory heat loss will increase. The O_2 mask reduced excessive expiratory heat loss induced by hypobaria, ensuring a uniform baseline for all subjects in both environments.

TREADMILL

The subjects walked on a treadmill with 0° incline. The treadmill was operated at a constant speed of 1.34 m/s (3 mph). The walking exercise was stopped at 45 minutes, or if the human use research criteria limits were reached, or when the subject voluntarily terminated. These last two conditions did not occur during the study.

ANALYSIS

Heat Loss

The dry heat exchange, H_{dry}, for a unit area of clothed skin surface, by the processes of radiation and convection, is [Nishi et al. 1975]

$$H_{dry} = h\left(\bar{T}_{cl} - T_a\right) = h \cdot F_{cl}\left(\bar{T}_{sk} - T_a\right) \qquad W{\cdot}m^{-2} \qquad \{1\}$$

where, h is the combined convective and radiant transfer coefficient, $h = h_c + h_r$. Burton's thermal efficiency factor, F_{cl}, is a measure of the resistance of clothing to heat flow [Gonzalez and Cena, 1985]. $\bar{T}_{sk}$, $\bar{T}_{cl}$, and T_a are skin, clothing surface, and ambient

temperature, respectively.

The convective transfer coefficient, h_c, is a function of air velocity and has been shown to be proportional to the barometric pressure, P_b [Gagge and Nishi, 1977].

$$h_c \propto \left(P_b/760\right)^{0.55} \qquad \mathrm{W{\cdot}m^{-2}{\cdot}K^{-1}} \qquad \{2\}$$

The evaporative transfer coefficient, h_e, in units of $\mathrm{W{\cdot}m^{-2}{\cdot}Torr^{-1}}$, is defined as

$$h_e = LR \cdot h_c = LR\left(\frac{760}{P_b}\right) \cdot h_c\left(\frac{P_b}{760}\right)^{0.55} = 2.2\,h_c\left(\frac{760}{P_b}\right)^{0.45} \qquad \{3\}$$

where, LR = Lewis relationship = 2.2 K/Torr at sea level [Gagge and Nishi, 1977].

Clothing Insulation

Surface Air Insulation. Surface air insulation is attributable to air held at the clothing surface boundary layer

$$I_a = \frac{\left(\bar{T}_{cl} - T_a\right) \cdot f_{cl}}{0.155 \cdot H_{dry}} \qquad \mathrm{clo} \qquad \{4\}$$

The clothing area factor, f_{cl}, typically increases by 20% ± 5% for each clo unit (1 clo = 0.155 $\mathrm{m^2{\cdot}K{\cdot}W^{-1}}$). For this study, f_{cl} was taken to be 1.2 for BDU and 1.4 for BDO [Breckenridge and Goldman, 1972].

Intrinsic Clothing Insulation. The intrinsic or basic clothing insulation is the insulation from skin to the clothing surface.

$$I_{cl} = \frac{\bar{T}_{sk} - \bar{T}_{cl}}{0.155 \cdot H_{dry}} \qquad \mathrm{clo} \qquad \{5\}$$

Total clothing insulation. Total clothing insulation is measured from the skin surface to the ambient environment.

$$I_{tot} = \frac{\bar{T}_{sk} - T_a}{0.155 \cdot H_{dry}} \qquad \text{clo} \qquad \{6\}$$

Skin Wettedness

Skin wettedness, **w**, describes the percentage of body skin wetted by sweat [Gonzalez and Cena, 1985].

$$\mathbf{w} = \left(P_{dp} - P_a\right) / \left(P_{sk} - P_a\right) \qquad \text{dimensionless} \qquad \{7\}$$

where, P_{dp}, P_{sk}, and P_a are water vapor pressure at dew point temperature, T_{sk}, and T_a, respectively.

STATISTICAL ANALYSIS

Statistical analysis consisted of repeated measures multiple analysis of variance (MANOVA). Tukey's test (significance level at α=0.05) was used as the *post hoc* test for the existence of significant difference between sea level and altitude data, and between clothing configurations. Unless noted otherwise, the differences pointed out in the discussion are statistically significant ($p<0.05$).

RESULTS

The data presented in Figures 1 - 7 are one minute averages of all eight subjects. On the time axis (horizontal axis), negative times (e.g., -10, -5) represent the period prior to the start of treadmill walk. Explicit positive times at the end of walk (e.g., +5, +10) represent the resting period after the treadmill exercise. The times at which treadmill walk began and ended are also marked by two vertical time lines. In Figures 1 – 5, only the

sea level data are shown for ease of readability and discussion. Figures 6 and 7 include both the sea level and altitude data.

The regional skin temperatures were combined to compute a weighted average skin temperature, $\bar{T}_{sk}$, in Figure 1. The weights used were based on the approximate percentage of total body skin surface area of each body segment: head 8%, chest 18%, back 18%, upper arm 8%, lower arm 8%, thigh 20% and lower leg 20% [Nishi et al. 1975]. A weighted clothing temperature, $\bar{T}_{cl}$ in Figure 2, was similarly computed using the same weighting factors.

Intrinsic clothing insulation, I_{cl} in Figure 3, and total insulation, I_{tot} in Figure 4 were computed using Equations {5} and {6}, respectively. There was no clothing insulation graph for the nude configuration in Figure 3. In Figure 4, the I_{tot} for the nude configuration simply represents the surface air insulation, I_a, described by Equation {4}.

Skin wettedness, **w** in Figure 5, was computed using Equation {7}. From Equation {7}, **w** is a function of P_{dp}, P_{sk}, and P_a which are, in turn, derived from T_{dp}, T_{sk}, and T_a, respectively. Therefore, skin wettedness **w** represents data independent of $\bar{T}_{cl}$.

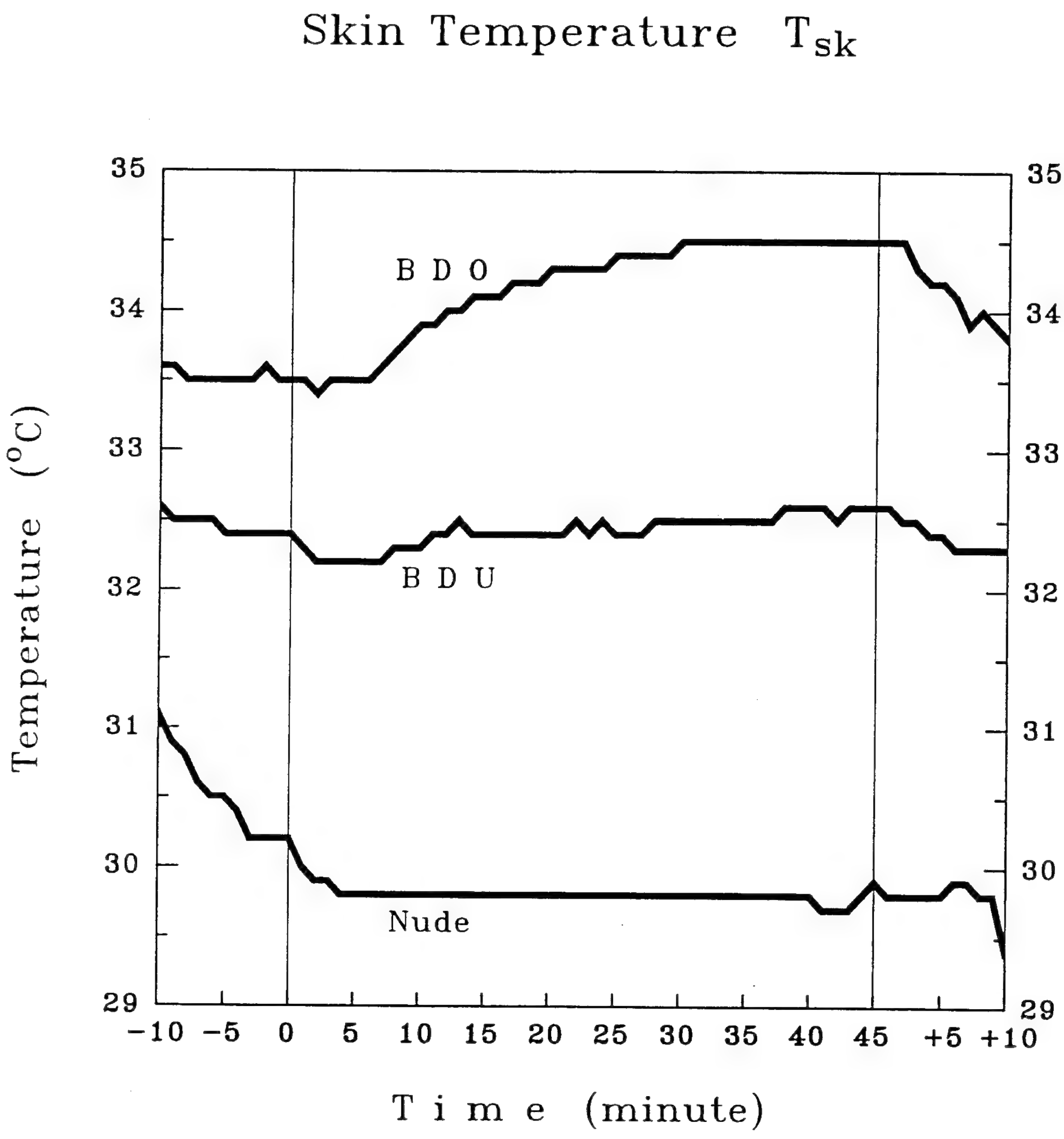
Figures 6 and 7 show that the same $\bar{T}_{cl}$ increase after the cessation of physical activity is also observed at the altitude environment. Figure 6 shows the I_{cl}, $\bar{T}_{cl}$, and $\bar{T}_{sk}$ data of BDU. Figure 7 shows the same parameters for the BDO.

DISCUSSION

SKIN TEMPERATURE

In Figure 1, an initial decrease in $\bar{T}_{sk}$ was seen in the pre-walk rest period. This decrease consisted entirely of convective heat loss. The decrease was largest for the nude, smaller for BDU and almost none for the BDO configuration, consistent with the increasingly higher clothing insulation values. After the start of the treadmill walk, steady-state (equilibrium) conditions were reached within five minutes for nude, in 15 minutes for BDU, and in 30 minutes for BDO.

Figure 1



Skin Temperature T_{sk}
35
34
33
32
31
30
29
B D O
B D U
Nude
Temperature (°C)
−10 −5 0 5 10 15 20 25 30 35 40 45 +5 +10
T i m e (minute)

CLOTHING TEMPERATURE

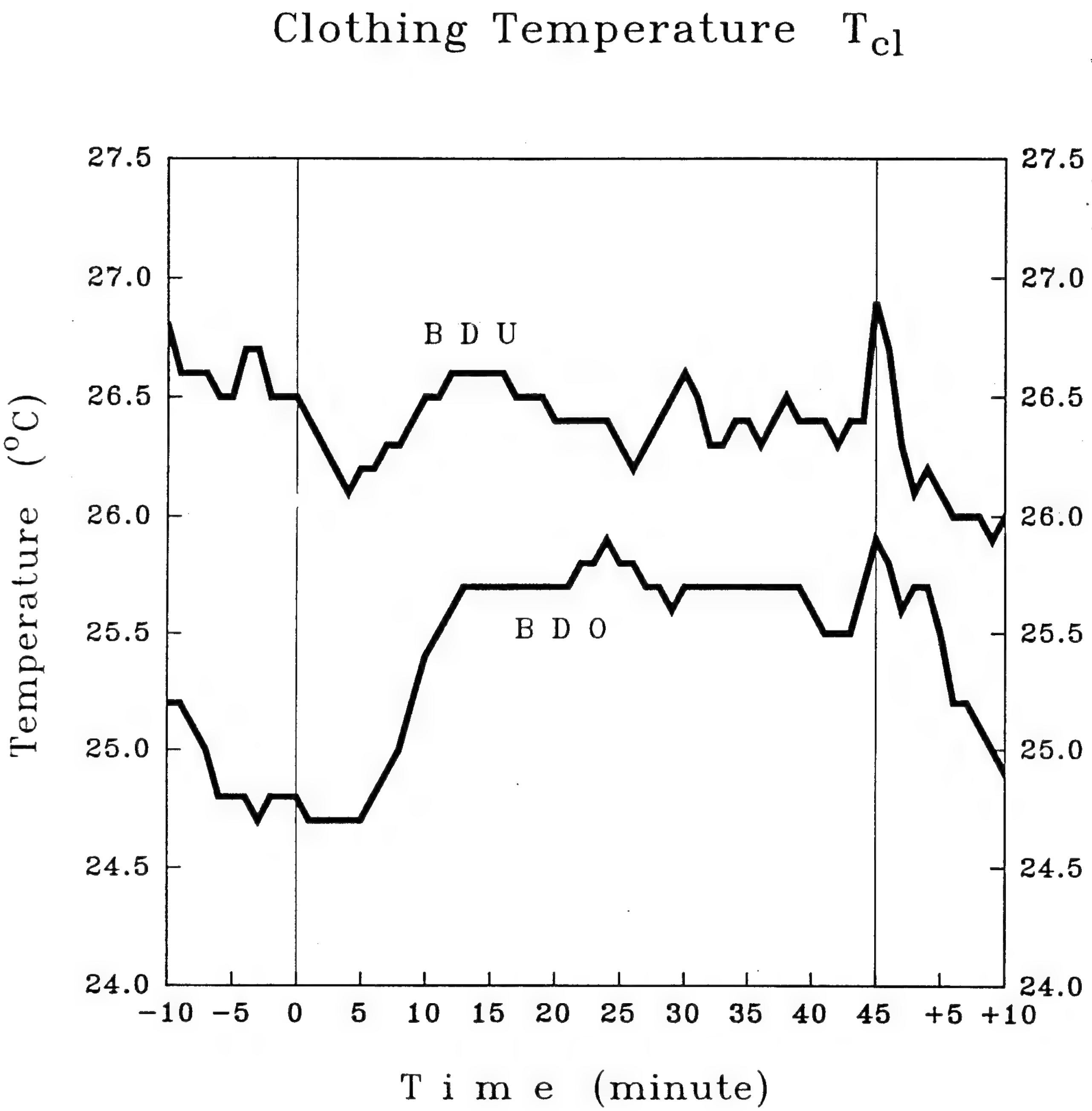
In Figure 2, $\bar{T}_{cl}$ of BDU was distinguished by a sharp increase immediately following the cessation of treadmill walk. This transient increase was approximately 0.5°C. The BDO ensemble also exhibited a corresponding increase, but slightly less in magnitude at 0.4°C. Since there was no parallel spike in $\bar{T}_{cl}$ at the start of the treadmill walk and no corresponding post-walk spike for $\bar{T}_{sk}$ (in Figure 1), it is reasonable to accept the observation as real event stemming from the cessation of the treadmill walk.

One probable cause of the observation would be the release of stored heat just after walking had ceased. Since there was no corresponding change in $\bar{T}_{sk}$, this large heat storage was not metabolic in its immediate origin, i.e. it was not released through the skin surface. Had this heat been released from the body core, there would have been a drop in $\bar{T}_{sk}$. If it did not come from the body tissue, the only possible place where heat could be held was within the air mass between the BDU/BDO and the skin surface. When walking stopped, this stored heat was released. The large temperature gradient between skin surface (at 32.6°C inside BDU and 34.5°C inside BDO) and ambient air (at 22°C) forced the heat flow outward resulting in the transient increase in $\bar{T}_{cl}$, but not in $\bar{T}_{sk}$.

PUMPING EFFECT

Another view of the heat storage within air mass between clothing layers is through the mechanism described as the "pumping effect." [Olesen et al. 1982; Vogt et al. 1983] During walking, the swinging limbs and movement of the body trunk aid air exchanges within the clothing layers. The limb and body movement also facilitate air exchange/access through clothing apertures, such as the openings around the neck, waist and wrist areas, to the ambient environment. The pumping effect results in a reduction of clothing insulation. Alternatively, the pumping effect can be viewed as providing, in effect, extra capacity of heat storage within the clothing layers. While walking, a steady state is achieved that incorporated the pumping effect. This equilibrium condition was disrupted when walking stopped. Without the additional ventilation of the pumping effect, heat trapped within clothing layers was released to the ambient environment. Again, the observed transient $\bar{T}_{cl}$ increase was the result.

Figure 2



Clothing Temperature T_{cl}
B D U
B D O
27.5
27.0
26.5
26.0
25.5
25.0
24.5
24.0
Temperature (°C)
−10 −5 0 5 10 15 20 25 30 35 40 45 +5 +10
T i m e (minute)

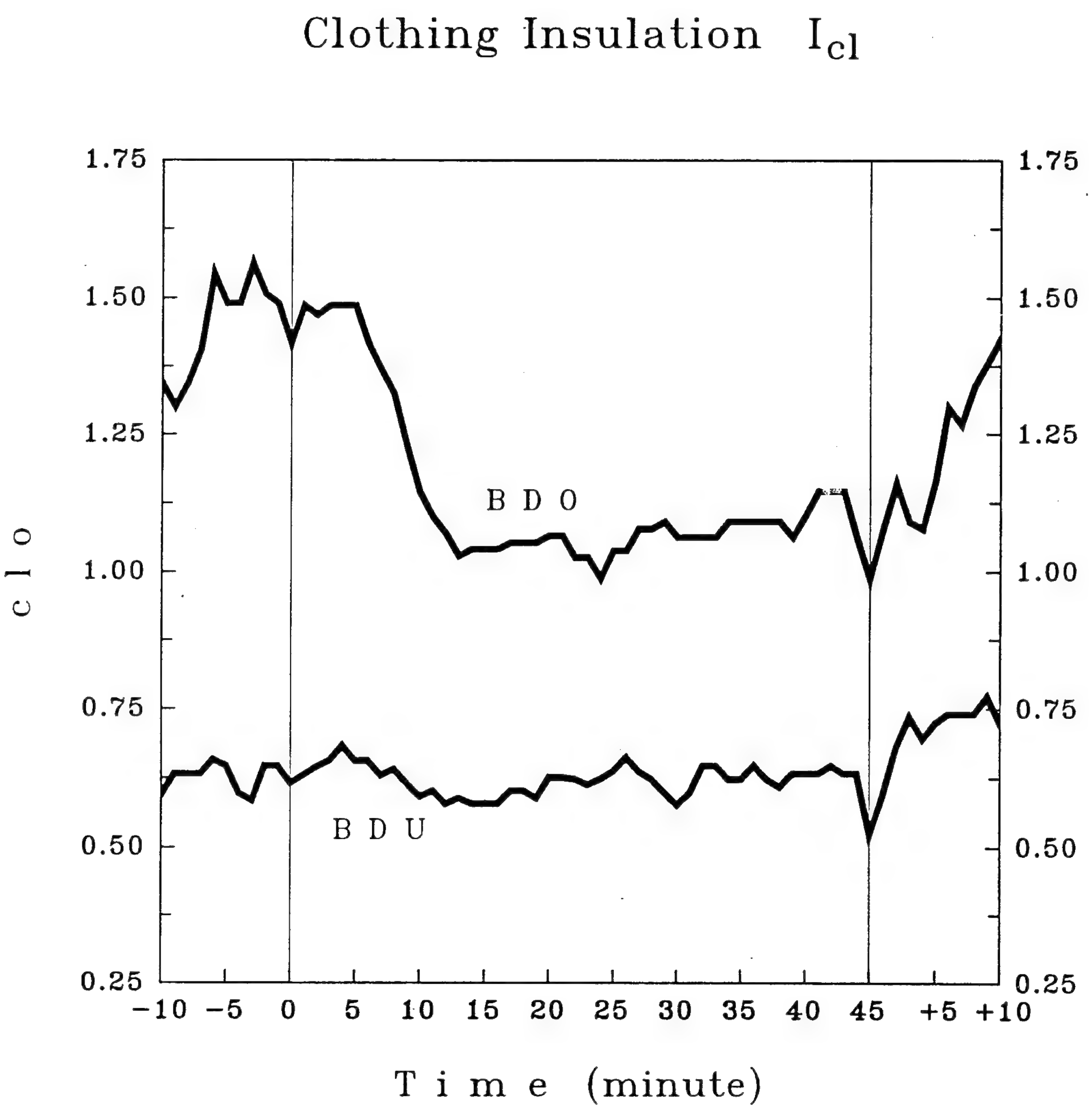
CLOTHING INSULATION

The intrinsic clothing insulation, I_{cl} in Figure 3, also reflects the sudden change in $\bar{T}_{cl}$ at the end of walking. However, the direction of the I_{cl} change does not seem to conform to what the pumping effect might have predicted. Comparing a stationary and a bicycling manikin, Olesen et al. [1982] reported that the pumping effect during bicycling resulted in a 0.06 clo to 0.10 clo decrease in I_{cl}. While Olesen used a moveable manikin, Nielsen et al. [1985] and Havenith et al. [1990] studied human subjects. Nielsen reported a 30% reduction in I_{cl} and Havenith saw a 15% I_{cl} decrease for walking, amounting to 0.30 and 0.13 clo reduction, respectively. The garments worn by Olesen's manikin, and Nielsen's and Havenith's subjects were similar in insulation values to the BDU used in this study.

In Figure 3, the I_{cl} of BDU shows a decrease of approximately 0.11 clo when the walking motion suddenly stopped. For the BDO, the effect was more moderate, only a 0.08 clo decrease was observed. However, if pumping indeed decreases the thermal insulation, then when movement stopped, a sudden <u>increase</u> in I_{cl} would be predicted. Yet, in Figure 3, I_{cl} shows a sudden <u>decrease</u>. It is worth emphasizing that the results reported in this study appeared to be transient in nature whereas Nielsen's [1985] and Havenith's [1990] data were from steady-state conditions.

The available data on the pumping effect are not in consensus. While reports cited above showed decreases in I_{cl} by pumping, Vogt et al. [1983] reported that pumping could either increase or decrease the resultant clothing insulation depending on the ambient air temperature. Nielsen [1985], however, disputed the accuracy of Vogt's data. It could be that there is a transitory as well as a steady-state phase to the pumping effect, which could account for the discrepancy in the findings when looking at the effect only in steady state.

Figure 3



Clothing Insulation I_{cl}
1.75
1.50
1.25
1.00
0.75
0.50
0.25
clo
B D O
B D U
−10 −5 0 5 10 15 20 25 30 35 40 45 +5 +10
T i m e (minute)

PENDULUM EFFECT

The transient increase in clothing insulation is also reflected in I_{tot} in Figure 4. In the nude configuration, I_{tot} simply represents I_a. Walking caused a thinning of the body surface air layer and decreased I_a by 0.02 clo. Since there was no clothing, there could not be any pumping effect. This decrease in I_a has been termed the "pendulum effect" by Clark et al. [1974] Clark reported that the swinging limbs could increase convective heat transfer by as much as a factor of two. Therefore, it appears when walking on a treadmill, there are two possible effects, pumping and pendulum, operating. The two effects are not additive. In the unclothed state, there is the pendulum effect. When clothed, the pumping effect would dominate, either by eliminating or diminishing the pendulum effect.

SKIN WETTEDNESS

The skin wettedness data of Figure 5 were derived from T_{dp} and $\bar{T}_{sk}$, independent of the $\bar{T}_{cl}$ data. Skin wettedness also shows a post-walk increase that seems to support a pumping effect operating. In Figure 5, the BDU data show skin wettedness suddenly increased by 8.6% as the walking motion ceased. The sudden increase in skin wettedness could be explained by the sudden cessation of microclimate ventilation provided by the pumping motion. Unfortunately, no further support or clarification could be obtained from the BDO data. At the end of walk, the skin wettedness data (for the chest region) indicate complete saturation under the BDO.

REGAIN

Another possible factor that must be considered falls under the general category of regain. Regain involves the complex interaction between clothing material, and heat and vapor transports. Two processes: condensation and hygroscopic absorption, appear to be probable mechanisms because both have the potential of increasing the temperature of clothing fabrics.

Figure 4

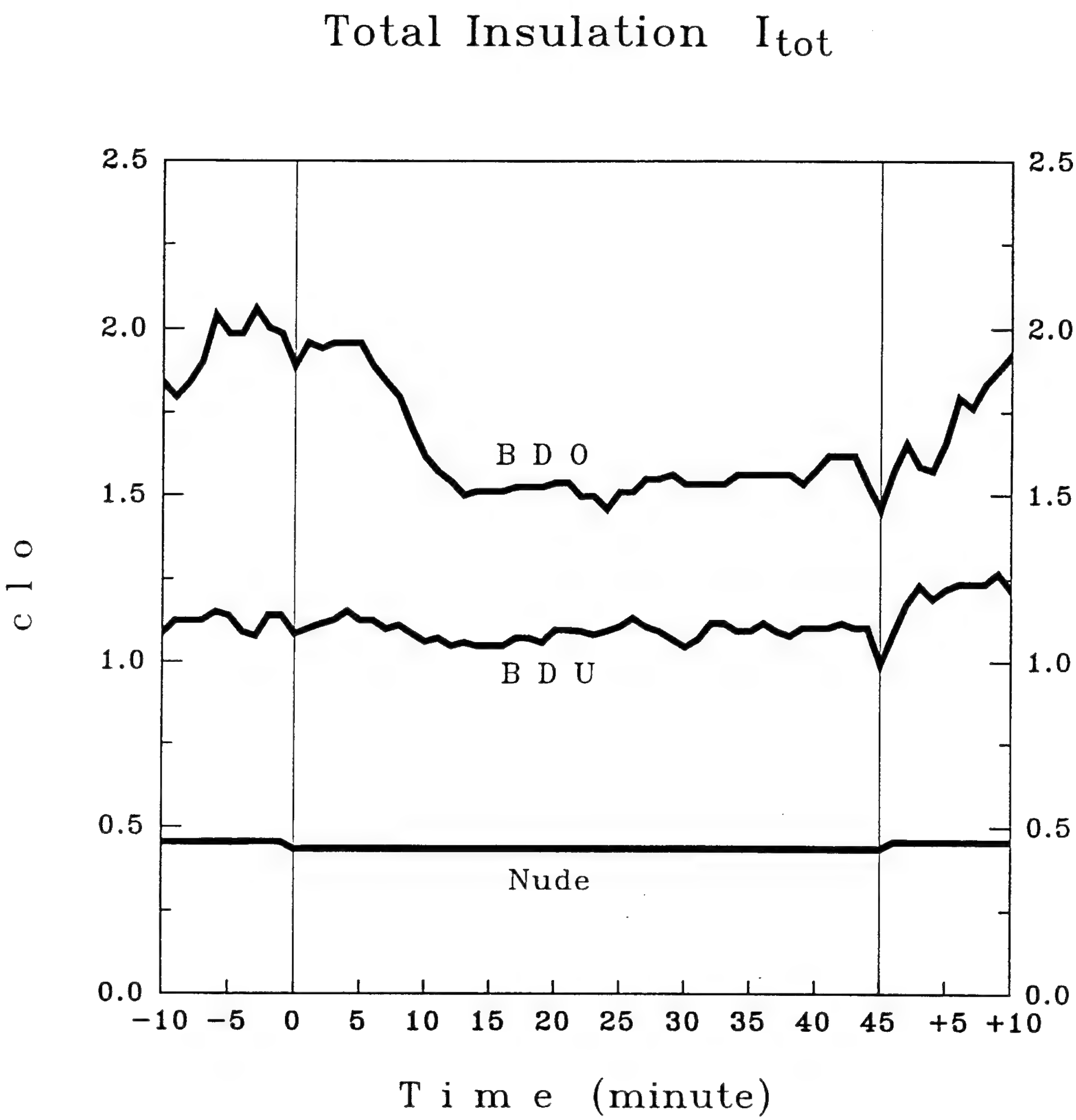
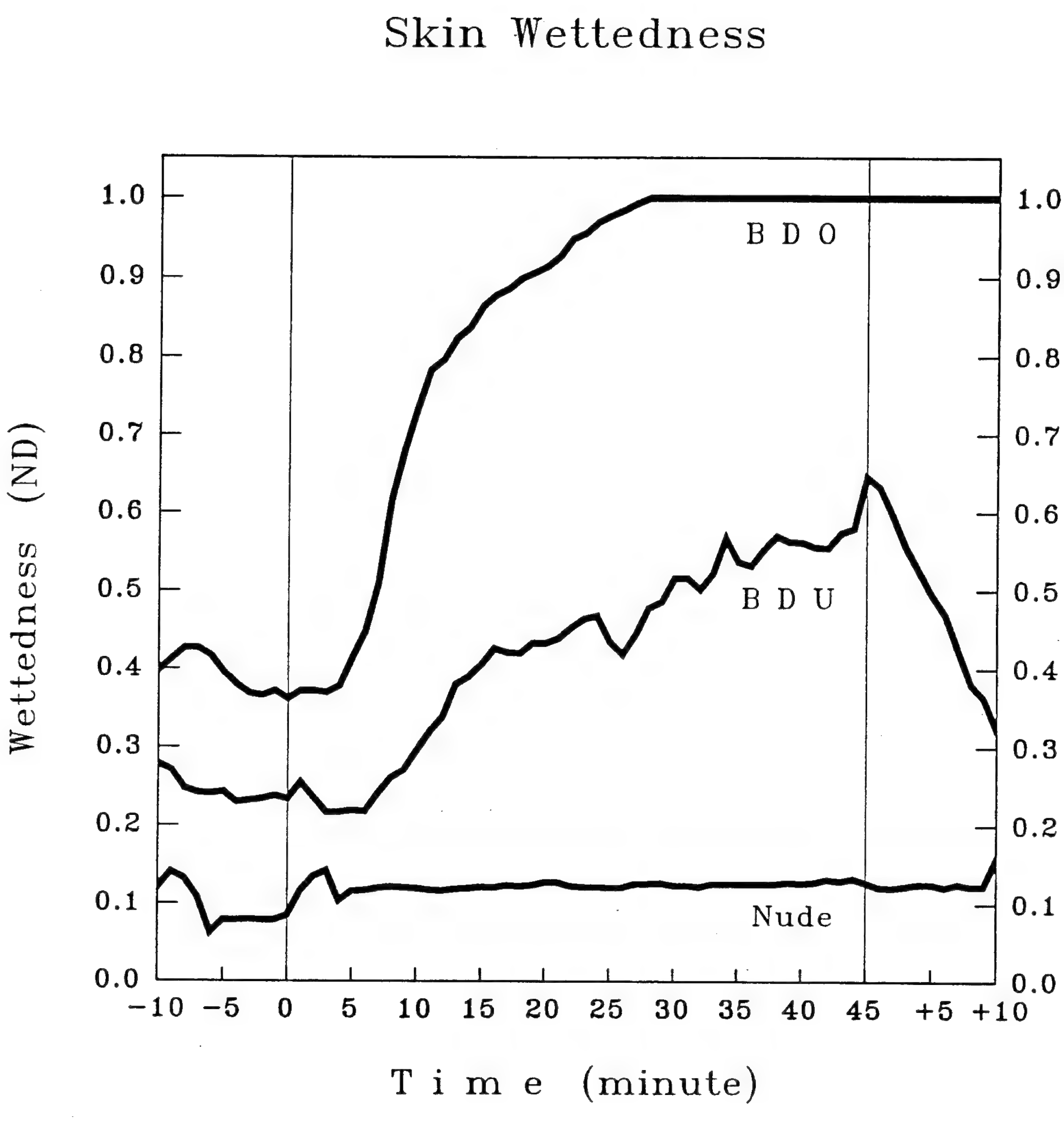

Total Insulation I_{tot}
2.5
2.0
1.5
1.0
0.5
0.0
c l o
B D O
B D U
Nude
−10 −5 0 5 10 15 20 25 30 35 40 45 +5 +10
T i m e (minute)

Figure 5


Skin Wettedness
Wettedness (ND)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
BDO
BDU
Nude
-10 -5 0 5 10 15 20 25 30 35 40 45 +5 +10
Time (minute)

Condensation of water vapor within clothing is likely to occur when the skin temperature is high and the ambient temperature is low, the exact condition created in this study. Condensation liberates heat thereby increases the temperature of the clothing fabric. However, condensation is possible only when conditions of saturation vapor pressure exists [Farnworth, 1986]. In the case of the BDU, the skin wettedness data of Figure 5 suggest that a state of water vapor saturation was probably not present at the end of treadmill walk. Complete saturation was more likely to be prevalent for the BDO ensemble, but less likely for the BDU.

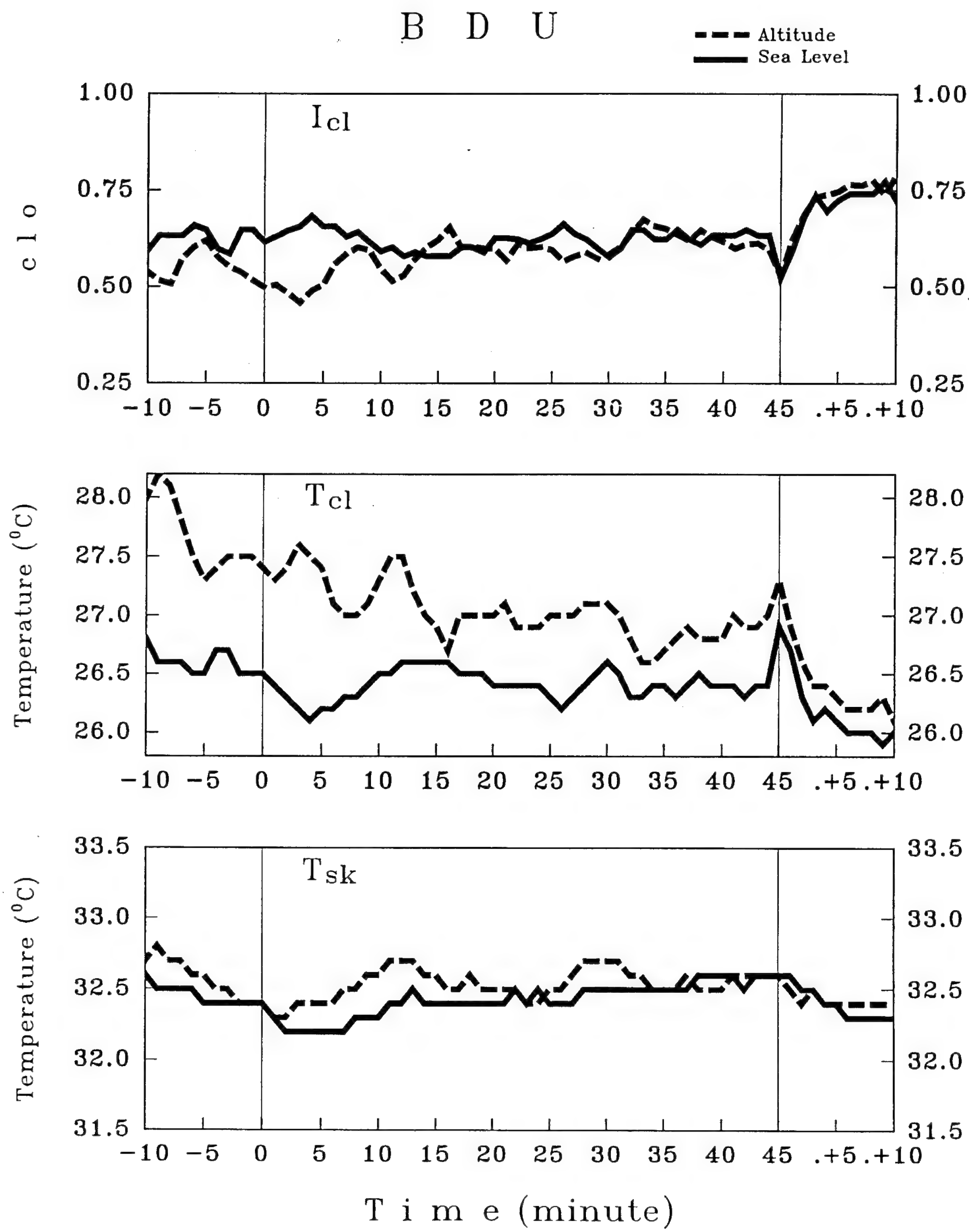
The physical process of hygroscopic absorption also liberates the heat of vaporization, hence could raise the clothing temperature. Furthermore, hygroscopic absorption is a transitory effect and can occur at any water vapor pressure level [Farnworth, 1986]. This mechanism would seem to be ideal to explain the observed transient increase in $\bar{T}_{cl}$ in this study. Nevertheless, this process is highly material dependent. Strongly hygroscopic material, such as wool, have been shown to exhibit regain [Holmér, 1985; Woodcock, 1962b], but reports of significant regain by the nylon/cotton twill of BDU and BDO are currently lacking.

BAROMETRIC PRESSURE

The observations at sea level were also found in the altitude testings. As Figures 6 and 7 show that similar large $\bar{T}_{cl}$ increase and the lack of a corresponding change in $\bar{T}_{sk}$ were also present after walking stoppage, in the hypobaric environment. This transient heat transfer through clothing, immediately after the cessation of activity, does not appear to be barometric pressure dependent.

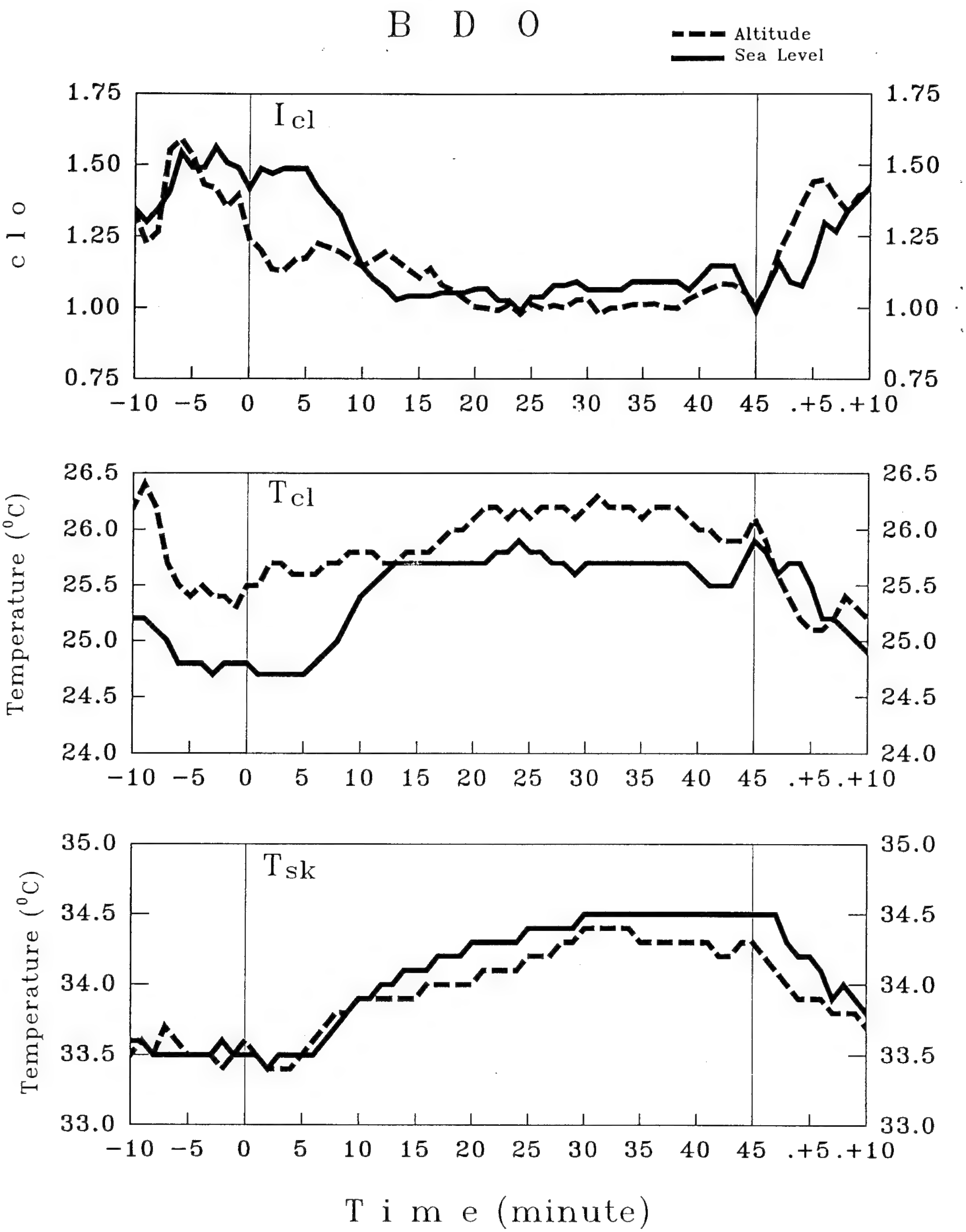
It should be noted, in general, hypobaria did contribute to a difference in $\bar{T}_{cl}$ between the two environments. In Figures 6 and 7, $\bar{T}_{cl}$, but not $\bar{T}_{sk}$ and I_{cl}, shows statistically significant difference between sea level and altitude data. The higher $\bar{T}_{cl}$ at sea level, for both BDU and BDO, could be attributed to diminished convective transfer at altitude.

Figure 6



B D U
Altitude
Sea Level
Icl
clo
1.00
0.75
0.50
0.25
-10 -5 0 5 10 15 20 25 30 35 40 45 .+5 .+10
Tcl
Temperature (°C)
28.0
27.5
27.0
26.5
26.0
-10 -5 0 5 10 15 20 25 30 35 40 45 .+5 .+10
Tsk
Temperature (°C)
33.5
33.0
32.5
32.0
31.5
-10 -5 0 5 10 15 20 25 30 35 40 45 .+5 .+10
Time (minute)

Figure 7


B D O
Altitude
Sea Level
Icl
clo
1.75
1.50
1.25
1.00
0.75
-10 -5 0 5 10 15 20 25 30 35 40 45 .+5 .+10
Tcl
Temperature (°C)
26.5
26.0
25.5
25.0
24.5
24.0
-10 -5 0 5 10 15 20 25 30 35 40 45 .+5 .+10
Tsk
Temperature (°C)
35.0
34.5
34.0
33.5
33.0
-10 -5 0 5 10 15 20 25 30 35 40 45 .+5 .+10
T i m e (minute)

BDU—BDO COMPARISON

The observed post-walk transient thermal effects, i.e. increase in $\bar{T}_{cl}$, were higher for BDU than for BDO, at both sea level and altitude environments. The difference was 0.2°C in both environments, as the chart below shows.

Increase in $\bar{T}_{cl}$ (°C)	BDU	BDO
Sea Level	0.5	0.4
Altitude	0.3	0.2

It is not exactly clear why the BDO ensemble showed a more moderate effect. One logical explanation would be the obvious difference between BDU and BDO, including the higher thermal insulation of BDO and the more complex fabric matrix necessary to incorporate the impregnated material of the BDO. The BDU allows higher ventilation. Presumably, in the post-walk period, the stored heat passed through the BDU more easily than the BDU+BDO combination (since BDO was worn over BDU). Hence, higher $\bar{T}_{cl}$ was observed with BDU. However, the data do not conform wholly to this scenario. More retained heat under the BDO would mean an inevitable increase in $\bar{T}_{sk}$, but $\bar{T}_{sk}$ did not show an increase under BDO (in Figure 1).

In a multi-layered clothing ensemble, a large volume of trapped air will result in a high thermal resistance. However, if air in the interstices between the fibers is replaced by molecular water, particularly from heavy sweating during exercise, the thermal resistance of the clothing ensemble is reduced due to the higher thermal conductivity of water. This offers an alternative explanation for the observed lower $\bar{T}_{cl}$ spike for BDO. The higher insulation of the BDO created a much wetter environment under the BDO than under the BDU. Therefore, less heat was actually retained within the wetter clothing layers under BDO. As a result, when the walking activity stopped, less stored heat was available to be released. Hence, a lower $\bar{T}_{cl}$ spike for BDO than for BDU.

A more probable explanation also involves moisture buildup. The skin wettedness was 100% (**w**=1.0) for BDO starting at the 30-minute mark of the treadmill walk. The

inner clothing layer was, very likely, sweat soaked. Wet clothing tends to cling to the skin thus impedes ventilation. The pumping effect and internal convective heat exchange was less effective during walking. Therefore, the actual reduction in I_{cl} by pumping was not as pronounced, translating to less heat storage. When walking stopped, less heat was available to be released and the transient increase in $\bar{T}_{cl}$ also was less.

CONCLUSION

A sharp increase in $\bar{T}_{cl}$ was observed during the transient period immediately following the cessation of a treadmill exercise. This increase was observed for both clothing ensembles, BDU and BDO. Clothing insulation values for both BDU and BDO reflected this transient effect. Because there was no corresponding change in $\bar{T}_{sk}$, it appears that the effect was not physiological in origin. There also does not appear to be a barometric pressure effect, as the increase in $\bar{T}_{cl}$ was observed at both sea level and a hypobaric environment. A probable explanation is a post-walk release of heat stored within the clothing layers. Alternatively, the pumping effect of clothing during walking could be used to explain the heat storage. When walking stopped, the stored heat was forced outward by the large temperature gradient between skin temperature and ambient temperature. The result was a transient increase in $\bar{T}_{cl}$ (coupled with a decrease in clothing insulation value I_{cl}), while the immediate skin temperature was not appreciably changed. The phenomenon of regain was also explored. Regain appears to be a less probable mechanism than a heat storage model.

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